DESIGN OF A COMPACT, LIGHTWEIGHT PULSED HOMOPOLAR GENERATOR POWER SUPPLY

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Summary

The Center for Electromechanics at The University of Texas at Austin (CEM-UT), funded by the U. S. Army Armament Research and Development Command (ARRADCOM) and the Defense Advanced Research Projects Agency (DARPA), has designed and begun construction of a compact, lightweight homopolar generator (HPG) that can be used as a portable field power supply. Nominally a 6-MJ, 750-kA generator, this machine will significantly advance the state of the art in terms of energy density in an inexpensive machine designed for production. The mechanical and electrical design of the machine, which is based on the all-iron-rotating (A-I-R) configuration, is discussed. Fabrication has begun and the machine should be operable by January 1982.

Introduction

Inertial energy storage with homopolar conversion, using a slow discharge, iron-cored machine, is an attractive pulsed power supply candidate for a system whose primary energy storage requirements are high energy density (MJ/m^3), high peak power (multimegawatt), very high current (MA), the ability to be repetitively pulsed, good efficiency, and reliability. Typically, HPGs are inexpensive, simple, rugged, and reliable.

However, HPG power supplies have tended to be large, rather bulky, fixed laboratory installations. Therefore, CEM-UT is building a compact, lightweight portable pulsed HPG that will be operable in a field application.

Slow discharge, iron-cored HPGs[1] have traditionally suffered in terms of energy density because a major portion of the magnetic circuit is stationary (back-iron), and contributes only to the mass and volume of the machine without contributing to the stored energy. (Fig. 1.) A new homopolar magnetic circuit, the A-I-R configuration, provides the opportunity to rotate essentially all the magnetic circuit, maximizing the stored energy density. The machine being built will use the A-I-R geometry to significantly advance the state of the art in terms of specific energy and power density. It will also serve as a demonstration of the applicability of the homopolar principle as a portable pulsed power supply.

A-I-R HPG Machine Design

Operating Parameters

Using the basic A-I-R geometry, a single rotor machine, shown in Figure 2, which weighs about 3,000 lbs, is being built.

Calculated values of the internal parameters of the machine are listed in Table 1. These parameters were calculated for an outer slip ring speed of 220 m/s (6,200 rpm). CEM-UT has successfully operated brushes at this speed. However, the machine is being built to be operated at 8,500 rpm, which results in an outer slip ring speed of 300 m/s.

Using a machine with the listed specifications to charge an inductive load, the calculated current and voltage waveforms, neglecting losses, are shown in Figure 3.

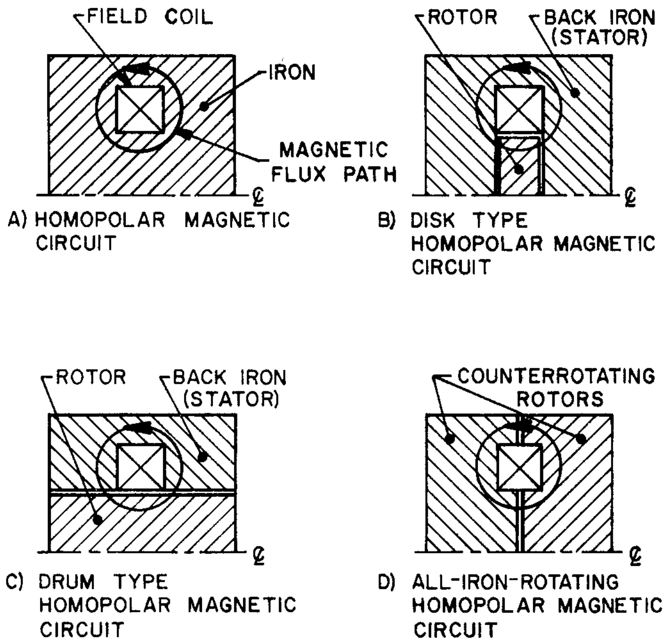

Fig. 1. Homopolar Magnetic Circuits

TABLE 1

A-I-R HPG SPECIFICATIONS

Stored Energy	6.26 MJ
Rotational Speed	654 rads/s
Capacitance	4468 F
Internal Resistance	6 μΩ
Internal Inductance	0.03 μH
Voltage	53 V
Magnetic Flux Density	1.8 T
Field Coil	70,000 A-t
Armature Current	750,000 amps

Machine Description

The A-I-R HPG has a 68 cm diameter, 40 cm thick rotor that is shaped for a constant magnetic flux path. The steel rotor weighs about 1,600 lbs and is supported radially by heavy-duty needle bearings and axially by angular contact ball bearings.

The 1.8 T magnetic field is supplied by a 70,000 amp-turn room temperature copper coil mounted in the steel stator. The magnetic field will be applied after the rotor is at speed and it will take several seconds to reach 1.8 T.

Current will be collected by two sets of both inner and outer brush mechanisms which connect the two rotor halves in series. This permits two voltage generating paths through the applied magnetic field.

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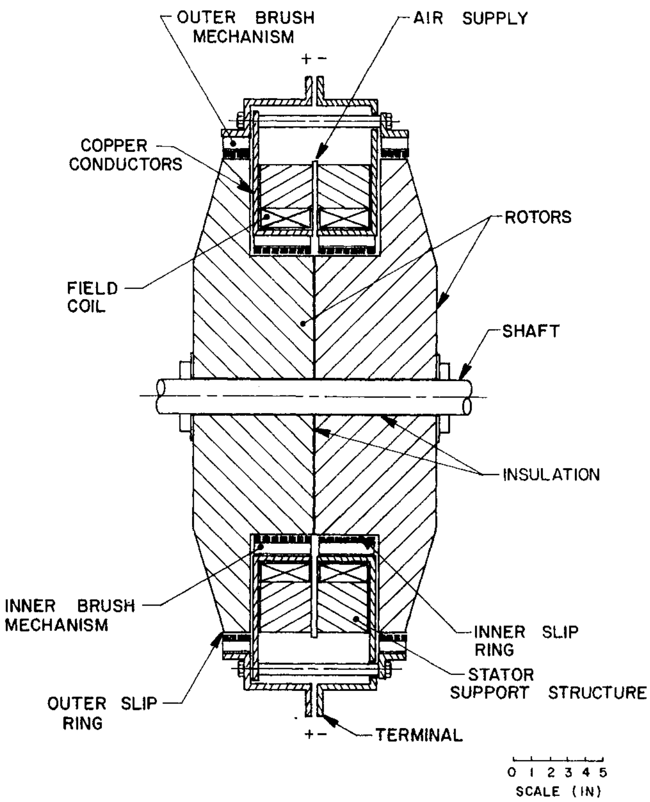

Fig. 2. 6.25 MJ A-I-R HPG cross section

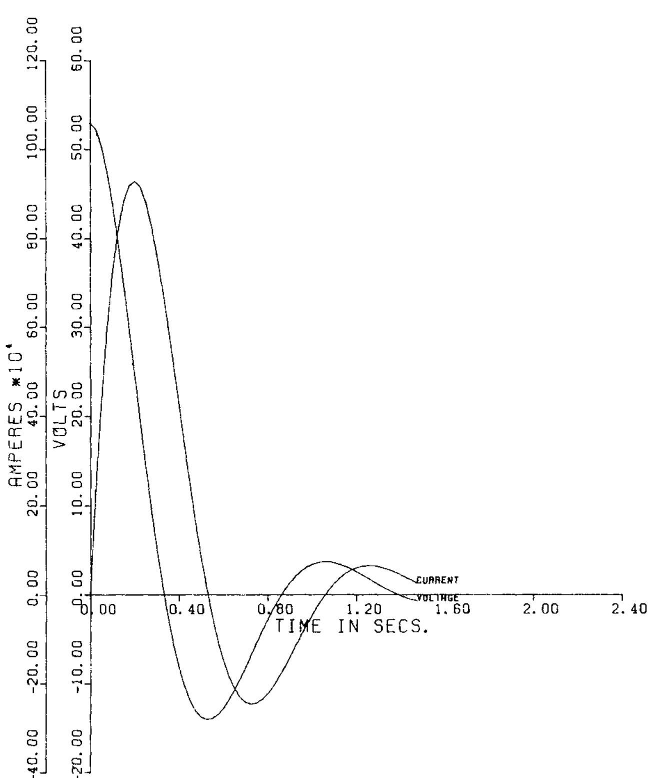

Fig. 3. Current and Voltage vs. Time for a 6.26 MJ, 4,468 F HPG Charging a 5.4 μH, 27 μΩ Load

An auxiliary power supply system will be mounted on the same portable frame as the HPG. This auxiliary package will have a prime power source driving the required auxiliary hydraulic and electric power supplies, making the overall machine package a realistic demonstration of a field portable system.

Rotor-Shaft Assembly

In the A-I-R HPG configuration the stator support structure houses the inner brush mechanism and the field coils (Fig. 2). To assemble the machine, the rotor must be split into halves and fitted around the structure. In addition, the rotor halves must be removed to perform maintenance on the field coils or the inner brush mechanism. Furthermore, the rotor halves must be insulated from each other to permit two voltage generating passes through the externally applied magnetic field.

In view of the rotor assembly restrictions, one rotor half will be shrunk fit into place while using a hydraulic shrink fit technique to assemble the remaining half. A drawing of the proposed rotor assembly configuration appears in Figure 4. In this scheme, the right half of the rotor having an insulated ceramic face will be shrunk onto a ceramic-coated shaft. Once the right rotor half is in place, the left side of the rotor will be expanded hydraulically and slid into position, thus completing the rotor assembly. The second rotor half can be removed at any time using the same technique.

At the A-I-R design speed of 220 m/s (6,242 rpm) the relative diametral growth between rotor bore and shaft is 0.0060 inches. Using a 100 percent factor of safety, the required initial interference is 0.0120 inches. This is a conservative design that allows the machine to be run at speeds in excess of the design goals if desired. (At 300 m/s, approximately 3,000 psi interference pressure will still be present between the shaft and rotor bore.)

The 0.012-in interference produces an interference pressure of approximately 44,000 psi at the contacting surfaces. The maximum combined stress resulting from this pressure occurs at the inner diameter of the rotor and is 78,250 psi. At the design speed of 220 meters per second this stress increases to a maximum value of 81,750 psi. This is a clear advantage of the interference fit; the combined stress remains fairly constant over the operating speed range of the

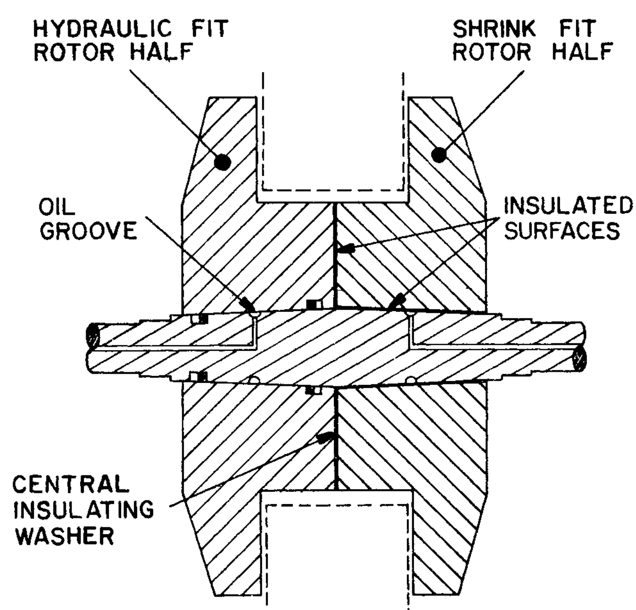

Fig. 4. A-I-R Rotor Assembly

machine. At zero speed, the stresses present are due entirely to the initial interference between the shaft and rotor bore. As the machine speed increases, the interference is decreased, lowering the stress level due to the interference pressure. Concurrently the stresses due to centrifugal effects in the rotor increase with speed, keeping the total stress level fairly constant. This effect is particularly advantageous from a fatigue standpoint because the cyclic stresses are minimized.

To hydraulically assemble the rotor, the shaft and rotor surfaces are separated, not thermally as in a normal shrink fit, but by hydraulic pressure supplied by an external pump. The pressure is introduced to the shaft-rotor interface through a port and oil groove (see Fig. 4). High-pressure oil seals on both sides of the oil groove prevent leakage from the ends of the rotor. Once the pressure is applied the rotor bore expands, and the rotor half is hydraulically forced onto the tapered shaft. A port and oil groove on the shrink fit side of the rotor will allow disassembly of this rotor half if necessary. Since seals are not required for rotor disassembly, they are omitted on the shrink-fit side.

The hydraulic pressure necessary to separate the shaft and rotor bore is the same as the final interference pressure (44,000 psi). A hand-operated pump provides this high pressure.

Machine Structure

The machine support structure is made entirely of aluminum and consists of a one-inch thick aluminum ring that is shrunk fit onto the steel stator, twenty T-shaped crossbars that are welded to the one-inch thick aluminum ring, and two conical end plates that connect the crossbars to the bearing housings. (Fig. 5) The electrical output terminals are nested with twenty crossbars so that a continuous, coaxial terminal configuration is possible. This will result in evenly distributed conductor forces and minimum inductance.

By calculating the stiffness of the support structure, it is possible to determine the required bearing and bearing housing stiffness to obtain a critical natural frequency (ω_n) that is at least 20 percent higher than the desired operating speed. This machine is being designed to operate below its lowest natural frequency (subcritical).

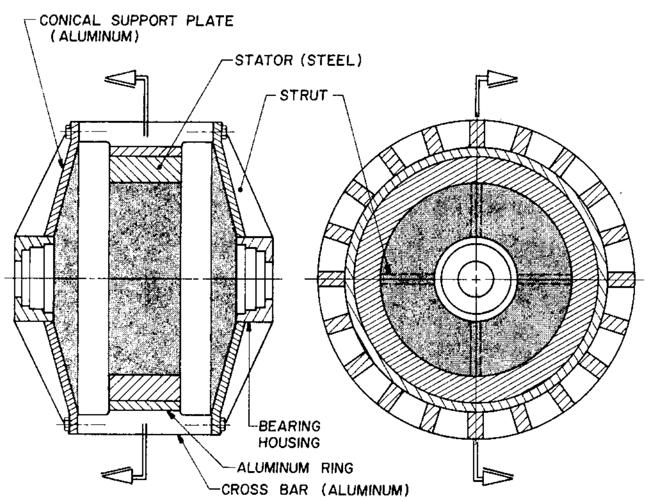

Fig. 5 A-I-R HPG Support Structure

Bearing Lubrication System

The bearing, shaft, and lubrication system is shown in Figure 6. The combined stiffness of the heavy-duty needle radial bearing is 1.4×10^7 lb/in for a 1,600 lb (rotor weight) preload. The L-10 life for these bearings is 1,8000 hours at 6,300 rpm. In the axial thrust direction a 1,400-lb preload is required to operate at 6,300 rpm, and the L-10 life is an acceptable 2,000 hours. To operate at 8,500 rpm will require a 17,000-lb bearing preload which will produce a 5.5×10^6 lb/in axial stiffness for the angular contact ball thrust bearings. With this preload, the L-10 life is 19 hours. Since rolling element bearings are inexpensive and easy to replace, several sets of thrust bearings--ground for different preloads, hence different stiffnessess--will be tested.

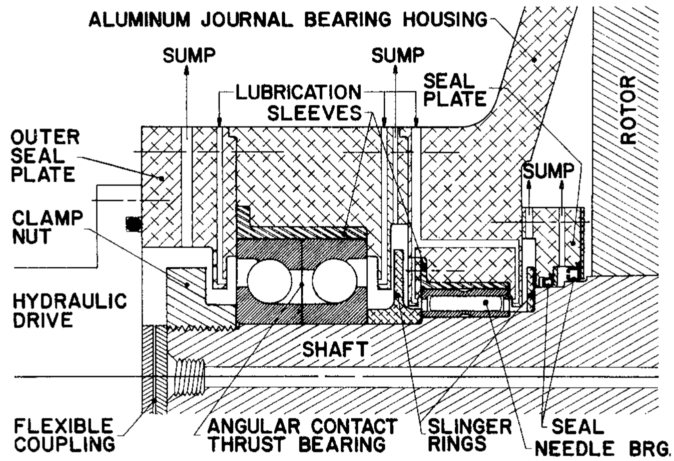

Fig. 6. Bearing, Shaft, and Lubrication System

A sophisticated lubrication system is needed to operate the bearings at these speeds and loads. As shown in Figure 6, each bearing will be lubricated by an oil jet having a flow rate sufficient to carry the generated heat out of the bearings. A sump system with multiple seals, slinger rings, and pumps will be used to rapidly remove the oil; this prevents pooling, which can cause severe heating problems.

Brush Mechanisms

Collecting and transferring the large currents inherent in a homopolar machine is a demanding task. The problems are compounded in the A-I-R configuration because of a radial height constraint on the inner brush mechanism. The radial height of the brush and actuating mechanism directly reduces the flux cutting area of the rotor, which in turn reduces the generated machine voltage. Also, one outer brush mechanism on this machine will be used as the current making switch --an untested concept that, if successful, will reduce the overall cost, complexity, and size of the power supply system.

The trailing strap design shown in Figure 7 has been used successfully on several CEM-UT machines. The design is dynamically stable and current compensating. Air cylinders are replaced by a new type of actuator that accomodates the radial height constraint and actuates a row of brushes simultaneously. This actuator is inexpensively produced and represents a substantial cost reduction over conventional air cylinders.

There will be 280 1/8-in thick x 3/4-in long x 7/16-in wide sintered copper-graphite brushes attached to a 0.093-in thick copper strap on each of the inner brush mechanisms and 300 similar brushes on each of the outer brush mechanisms. At 750,000 total amps the inner brushes, which operate at lower sliding velocity but must conduct slightly higher currents per brush, will each by carrying 2,678 amps at a brush current density of 8,163 amps/in^2. These conditions have

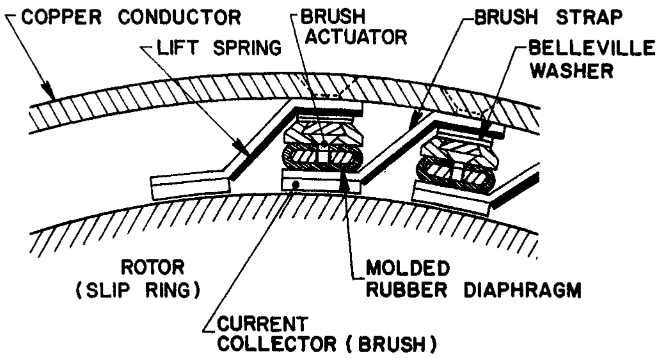

Fig. 7. A-I-R HPG Brush Mechanism

been exceeded on the CEM-UT 5-MJ HPG. The brush strap will have a temperature increase of approximately 50°C during a discharge, which is the highest ΔT in the machine.

It is desirable to minimize the mass of a brush to improve its ability to follow the rotor surface. However, this must be balanced against brush wear considerations to obtain a desired brush life. Experiments conducted at CEM-UT have indicated a conservative wear of <0.0001 in/cycle on steel. Using this rate and a desired life of 1,000 cycles, the brushes have been sized to be 0.125 in thick. Decreasing the brush thickness decreases the radial height of the brush mechanism and contributes to an increase in machine voltage as well as minimizing the bulk voltage drop associated with the brush material itself.

Field Coils

After determining the magnetic circuit, flux plots (Fig. 8) were run with field coils having 50,000, 60,000, 70,000, and 80,000 amp-turns. The plots show that at 50,000 amp-turns, and 220 m/s slip-ring speed, the machine will have an approximate open-circuit voltage of 48.52 volts; at 60,000 amp-turns, 50.50 volts; and at 70,000 amp-turns, 52.20 volts. However, increasing amp-turns past 70,000 does not significantly increase the voltage because of increased flux leakage. Therefore the field coil is being designed for 70,000 amp-turns but will probably run at 50,000 amp-turns.

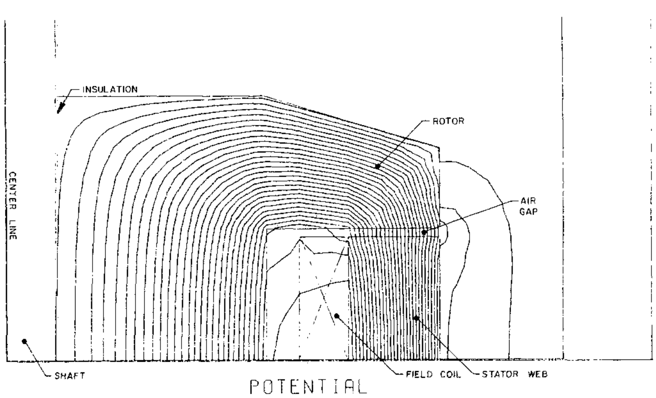

Fig. 8. Flux Plot - A-I-R HPG

The field coil has 84 turns of 0.23 inch square solid copper conductors insulated with a heavy coat of armored polythermalized insulation. This tough, inert insulation can withstand temperature increases of 200° C. The coils will be vacuum impregnated with an epoxy potting compound. Terminals of the coil will be plug-in Multilam (T.M.) connectors located between the two coil halves. The terminal access will be through the center of the stator in order to minimize field dissymmetry. These coils can be run either in series or in parallel and require a 30-V, 417-amp power supply per coil at the 70,000 amp-turn level. The coil will be run in a pulsed mode with a temperature rise of 10-15° C.

Magnetic Field Time Constant

Since the A-I-R homopolar generator is constructed from solid ferromagnetic material, diffusion of the magnetic field flux generated by field or armature mmf must be considered in circuit analysis of (a) the machine being self-excited (an attractive option for field applications) and (b) armature reaction becoming significant at high current levels.

A self-excited generator system has been investigated for field portable machines to reduce the size and weight of peripheral equipment. If the fundamental time constant of the rotor and stator material is significantly greater than the desired rise time of load current, however, self-excitation may not be feasible.

Eddy currents are generated in both the rotor and stator conductors to oppose any change in magnetic flux density. These eddy currents cause the field flux to lag the field current when the machine is excited. If a separate power supply is used to excite the field, a several second delay will be required before initiating the discharge to allow the applied axial field to reach steady state conditions.

The eddy currents that prevent the field flux from rising rapidly also prevent the field flux from changing instantaneously due to armature reaction. Calculations of circumferential magnetic field intensity due to armature current indicate that severe armature reaction would occur at these current levels under steady state conditions. For a relatively fast transient, however, the eddy currents prevent rapid demagnetization. Based on initial estimates of the fundamental diffusion time constant, the induced eddy currents should prevent severe armature reaction during a discharge.

This project is being funded by the U.S. Army, ARRADCOM, and DARPA. The machine, a 6-MJ 750-kA pulsed homopolar generator should be operating early in 1982. It will serve as a demonstration of the applicability of the homopolar principle as an inexpensive, portable, pulsed power supply.

References

1. T. M. Bullion et al., "5-MJ Homopolar Upgrade," proceedings of this conference.